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# Study of the $^{234}$U(n,f) fission fragment angular distribution at the CERN n_TOF facility

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**Abstract**
The angular distribution of the f ssion fragments (FFAD) produced in neutron-induced reactions of actinides have been measured with a f ssion detection setup based on parallel-plate avalanche counters (PPACs) at the Neutron Time-Of-Flight (n_TOF) facility at CERN. The main features of the setup and preliminary results are reported here for the $^{234}$U(n,f) reaction measurement showing a high concordance with previous data, while providing new results up to 100 MeV.

## 1 Introduction

A deeper knowledge on the reaction cross sections related to the Thorium-Uranium fuel cycle, such as the $^{234}$U isotope, is crucial for the development of New Generation nuclear reactors and the Accelerator Driven Systems (ADS). An accurate cross section of this nucleus is required for a detailed investigation of its f ssion barrier parameters, shedding some light on the Triple Humped Fission Barrier controversy.

The angular distribution of the fragments (FFAD) produced in the f ssion of an excited nucleus plays a role to achieve more accurate measurements of the f ssion cross sections. This is also an important observable to investigate the properties of transition levels close to the f ssion threshold [1, 2]. The directional dependence of f ssion fragments (FF) as a result from a transition state is related with its quantum numbers J, K and M (total spin and its projections on the nuclear symmetry axis and on a space-f xed axis). Since the $^{234}$U has zero spin and the neutron spin is $\frac{1}{2}$, only two values of M are allowed, which makes this nucleus a simple case to study.

The behaviour of the FFAD is of particular interest above several tens of MeV, where it has been predicted almost isotropic similarly to the case of proton-induced f ssion. However, recent experimental results [3] suggest a revision of this assertion.

In order to provide accurate data of neutron-induced reactions, a broad program of measurements is being performed at the CERN Neutron Time-of-Flight (n_TOF) facility. As a part of this program, measurements of neutron-induced reactions in $^{234}$U, $^{235}$U, $^{238}$U and $^{237}$Np have been carried out at the last campaign (2012) using a f ssion detection setup based on parallel-plate avalanche counters (PPACs) developed and built at the IPN-Orsay (France). Previous measurements with several isotopes were performed during the Phase I (2002 to 2003) and the Phase II (2010 to 2011) of the n_TOF project [4, 5]. The angular arrangement of the detectors and targets has been modif ed for the Phase II experiments with respect to the Phase I to cover all the angular range in the emission of the FF.

The results obtained for $^{232}$Th(n,f) with this new setup in the last campaigns of the Phase II conf rmed large variations of the anisotropy around the f ssion chances [6]. The $^{234}$U(n,f) cross section is higher than the $^{232}$Th(n,f), which makes this isotope a good candidate to study the vibrational resonances in the sub-threshold region, where the existing data show large anisotropy values. Above the threshold, the bibliography is scarce and only Leachman provides information up to 15 MeV [7–11].

This work presents the preliminary results of the FFAD analysis of the $^{234}$U(n,f) data. The anisotropy parameter has been calculated and compared with the available data up to 15 MeV, extending the analysis up to 100 MeV.

## 2 Experimental setup

The Neutron Time-of-Flight (n_TOF) facility at CERN is characterized by a white neutron source produced by spallation on a lead target of 20 GeV/c protons provided by the Proton Synchrotron (PS), covering the energy range from thermal up to 1 GeV. The long flight path (183.4 m) from the spallation target to the chamber containing the detectors and targets, located in the experimental area, offers the possibility to obtain high resolution measurements. Charged particles produced in the spallation reaction are removed from the beam using a sweeping magnet and two collimators are placed in the neutron path, the second of which, for fission reactions measures 8 cm diameter, defining the neutron beam profile. More detailed information about the n_TOF facility can be found in Ref. [12].

### 2.1 Parallel Plate Avalanche Counter detectors

The detection setup used to perform the measurements was constituted by parallel-plate avalanche counters (PPACs). Each PPAC consist in three electrodes, one central anode sided by two cathodes. The 3.2 mm gaps between the electrodes are filled with the non flammable gas Octafluoropropane ($C_3F_8$) at 4 mbar pressure.

The electrodes are composed of 1.7 $\mu$m Mylar foils covered by an aluminum layer. The anode is characterized by a very fast signal response, providing a time resolution better than 500 ps. Each cathode is segmented in parallel aluminum strips connected to a delay line in order to provide information about the position of the fission fragment hit in one dimension. Through the combination of two cathodes, with the strips placed perpendiculary between them, we can reconstruct the two dimensional position of the hit in the detector.

### 2.2 Targets

The targets used in this experiment consisted in a thin radioactive layer ($\sim$ 0.3 mg/cm$^2$) deposited as a 8 cm diameter disk in an aluminum foil of 2.5 $\mu$m (the first six targets) or 0.7 $\mu$m (the last three targets) thickness built at the IPN-Orsay. The deposition of the samples compounds in the aluminum backing was performed by electro-deposition. Three samples of $^{234}$U, one of $^{237}$Np and, as reference samples, two of $^{235}$U and three of $^{238}$U were used in this campaign.

The thickness and the mass distribution of the thick backing samples were measured by $\alpha$ spectroscopy and by Rutherford Backscattering Spectroscopy (RBS).

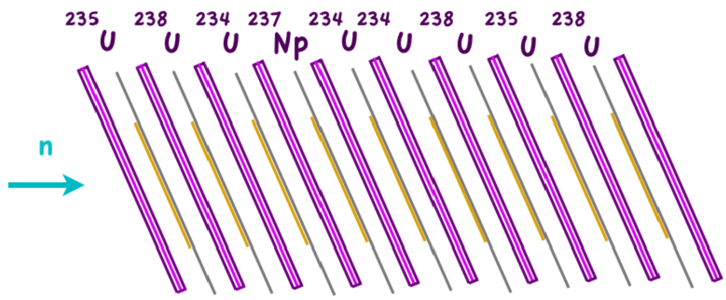


**Fig. 1:** Schematic top view of the PPACs and targets (2012 campaign).

The fission chamber containing the ten PPACs and nine targets in between consisted in a stainless steel cylinder filled with the gas at low pressure. The detectors and targets inside the chamber were tilted 45° with respect to the incident neutron beam in order to cover all the angular range (from 0° to 90°) and placed in an aluminum bottom supporting them, which distribution is shown in Fig. 1.

## 3 Data Analysis

The f ssion event identif cation is determined by the coincidence detection of the two FF by the PPACs f anking the target where the f ssion reaction takes place. The fast signal of the anodes is used for this coincidence technique, which allows to discriminate the $\alpha$ background and the spallation reaction products. The PPAC detectors are almost insensitive to gamma rays. The cathode signals were used to calculate the emission angle of the FF by means of the knowledge of the hit position in the detector. As was mentioned before, when the fragment reaches the cathode, the signal produced in one of the parallel aluminum strips is directed to the delay line and propagated along it in both directions. Because every PPAC is composed of two cathodes, with perpendicular strips between them, in the X and Y directions, we can obtain the two dimensional position of the FF hit in the detector. Since each target is f anked by two PPACs, knowing the points of both FF hits in each one of them and assuming that both fragments are emitted with 180° between them, we can design a vector $\vec{V}_{FF}$, and the beam direction is def ned by the vector $\vec{V}_{beam}$, see Fig. 2.

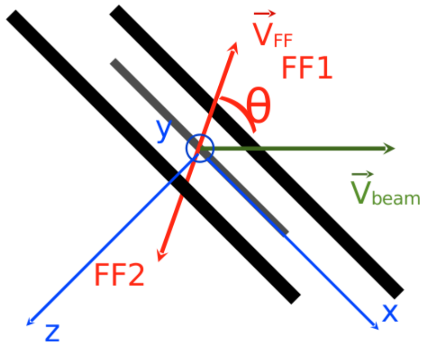


**Fig. 2:** Scheme of the reference frame used to reconstruct the trajectories of the FF, as is explained in Refs. [5,6].

The assumption that both FF are emitted back to back with an angle of 180° between them is valid because the error introduced by the momentum transfer in the angle measurement at large neutron energies is negligible as explained in Ref. [6].

Hence, the emission angle of the FF can be expressed through its cosine (cos$\theta$), which is calculated as the scalar product of both vectors, as given by equation (1).

$$cos\theta = \frac{\vec{V}_{FF} \cdot \vec{V}_{beam}}{|\vec{V}_{FF}| \cdot |\vec{V}_{beam}|} \tag{1}$$

### 3.1 Fission Fragment Angular Distribution (FFAD)

The number of emitted FF with an angle $\theta$ for a particular neutron energy is given by the expression:

$$W(E_n, \theta)_{emitted} = \Phi(E_n) \cdot N \cdot \frac{d\sigma(E_n, \theta)}{d\Omega} \tag{2}$$

while the number of detected FF is def ned as:

$$W(E_n, \theta)_{detected} = \Phi(E_n) \cdot N \cdot \frac{d\sigma(E_n, \theta)}{d\Omega} \cdot \epsilon(\theta, \phi) \tag{3}$$

where $\Phi(E_n)$ is the time-integrated neutron f uence over the full measuring time, N is the number of atoms in the sample, $d\sigma(E_n, \theta)/d\Omega$ is the differential cross section and $\epsilon(\theta, \phi)$ is the detection eff ciency.

The FFAD for different energy intervals can be expressed in terms of cos$\theta$, however to study the angular behaviour, an accurate value of the detection efficiency is required. Assuming that the efficiency is independent of the energy range and that the FFAD is isotropic in the resonance region, we can substract the dependence on the efficiency factor in the last equation dividing the angular distribution for each energy interval by that obtained below 1 keV.

The experimental FFAD (W($\theta$)/W(90°)) can been fitted by a sum of Legendre polynomials:

$$W(\theta)/W(90^{\circ}) = A_0 \cdot \left[1 + \sum_{L_2}^{L_{max}} A_L \cdot P_L(cos\theta)\right] \tag{4}$$

where L is the order of the polynomial (only even terms are considered) and $A_L$ are the coefficients, which are considered up to $4^{th}$ order. The best fit to the data has been chosen for every energy range depending on the $\mathcal{X}^2$ value.

### 3.2 The anisotropy parameter

The angular distribution behaviour in the edges depending on the neutron energy can be studied by means of the anisotropy parameter (W(0°)/W(90°)) which is defined in this case as:

$$W(0^{\circ})/W(90^{\circ}) = \frac{1 + A_2 + A_4}{1 - \frac{1}{2} \cdot A_2 + \frac{3}{8} \cdot A_4} \tag{5}$$

where the coefficients are obtained from the previous Legendre polynomial fit to the FFAD data.

Although this parameter does not provide a complete description of the angular distribution, it is a simple way of comparing our results with the existing experimental data.

## 4 Preliminary results

The present results correspond to the preliminary analysis of one of the three $^{234}$U targets.

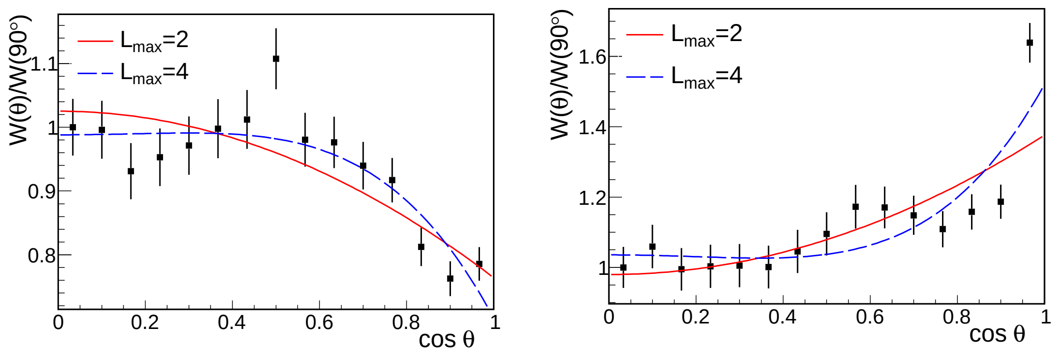


**Fig. 3:** Experimental FFAD of $^{234}$U(n,f) for the energy range E$_n$= $(0.46, 0.56)$ MeV (left panel) and for E$_n$= $(6.31, 7.08)$ MeV (right panel) fitted to the Legendre polynomials up to $4^{th}$ order.

The experimental FFAD fitted to the Legendre polynomials of $2^{th}$ and $4^{th}$ order are shown in Fig. 3 for two energy ranges. The error bars are related to the statistical uncertainty. The figure on the left panel corresponds to the energy range from 0.46 to 0.56 MeV. This distribution is side peaked, showing a minimum at the cosine equal to one. Otherwise, in the energy range from 6.31 to 7.08 MeV, the angular distribution is peaked at the cosine of the angle equal to one, which means that fragments are predominantly emitted in the beam direction.

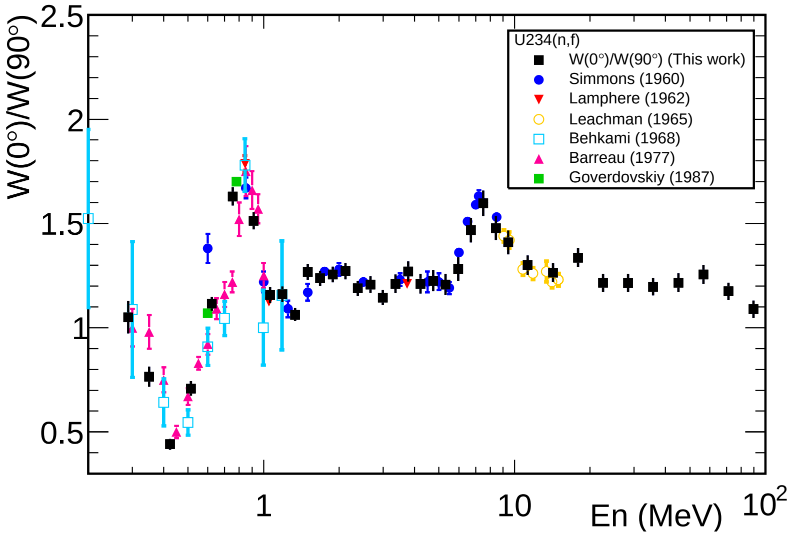


**Fig. 4:** Anisotropy parameter obtained in this work up to $E_n$=100 MeV for the $^{234}$U(n,f) reaction compared with previous measurements, Refs. [7–11].

The anisotropy parameter has been calculated for neutron energies up to 100 MeV and compared with other works, which provide data below 15 MeV, showing a good agreement with the previous measurements, as can be seen in Fig. 4.

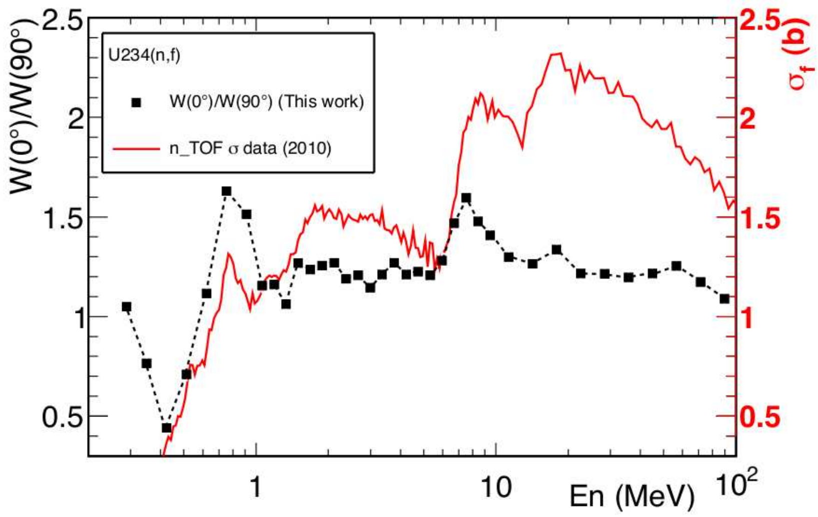


**Fig. 5:** Comparison between the anisotropy parameter obtained in this work up to $E_n$=100 MeV and the cross section data obtained in the n_TOF Phase I previous measurement by C. Paradela et al (2010), [4]

The comparison between the anisotropy parameter calculated in this campaign and the cross section data obtained in the n_TOF Phase I previous measurement by C. Paradela et al. [4], is shown in the Fig. 5. It can be seen that the main FFAD variations occurs at the openning of the f rst and second f ssion chances.

## 5 Conclusions and outlook

The method used in the present analysis was successfully proved with $^{232}$Th by D. Tarrío et al. in the earlier Phase II experiment at n_TOF [5, 6]. Preliminary results hold here correspond only to one target of $^{234}$U, showing a good agreement with the literature, which provide data of the previous experimental measurements up to 15 MeV, and extending them up to 100 MeV.

The analysis of the two $^{234}$U samples is in progress and it will continue with the $^{235}$U, $^{238}$U, and $^{237}$Np targets. The complete experimental data of the three $^{234}$U samples will increase the statistics providing a more detailed description of the FFAD. This will allow us to obtain a more precise value of the $^{234}$U(n,f) cross sections.

Experimental program on the thorium cycle isotopes will follow with the $^{231}$Pa measurement which is planned for the next f ssion campaign. It is expected during 2015, depending on target manufacture.

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